

Light Gluinos and Jet Production in $\bar{p}p$ Collisions

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Abstract

The impact of a light, long lived gluino on jet production cross sections in $\bar{p}p$ collisions is estimated. The effect is found to be relatively modest, particularly when gluinos are incorporated into the parton densities of the proton. Although a light gluino does enhance the production of jets at high E_T , the effect is insufficient, by itself, to explain the high E_T excess observed by CDF.

1 Introduction

In addition to those which have already been observed, the minimal supersymmetric standard model predicts a plethora of new particles. Among these new states is the superpartner of the gluon, a color octet Majorana fermion known as the gluino. It is generally believed that the superpartners of the known particles should have masses of order 10^{2-3} GeV, but experimental searches have yet to find any direct evidence for supersymmetry. Some authors, however, have argued that a very light gluino with a mass in the several hundred MeV range is difficult to exclude on the basis of present data [1, 2].

A number of experiments have searched for light gluinos. The persistently negative results obtained have been used to exclude large ranges of masses and lifetimes for this particle. These experiments include various beam dump experiments [3], searches for exotic particles in various mass and lifetime ranges [4], searches for gluino-containing hadrons produced in Υ and χ_b decay [5], and collider searches [6]. Taken at face value, these experiments exclude all but a few narrow windows for the light gluino. It has been argued, however, that the excluded range may have been overestimated [2, 7], and that sizable allowed regions remain.

Very recently, data from the Fermilab E761 experiment [8] have been re-analyzed to derive bounds on the production rate of gluino-containing baryons with lifetimes in the range 50 to 500 picoseconds. This experiment placed stringent constraints on the fraction of gluino-containing baryons that are produced when 800 GeV protons are incident on a copper target. The fraction is found to be less than about 10^{-5} for relatively light (~ 1.7 GeV) gluino containing baryons. However, the acceptance of the experiment is not sufficient to place as stringent bounds on the production fraction of heavier (~ 2.5 GeV) supersymmetric baryons.

There is some controversy regarding the exact mass and lifetime regions allowed for light gluinos. A fairly liberal estimate of the allowed regions may be found in Ref. [2]. It is argued there that gluinos which hadronize into gluino-gluon bound states of mass less than about 2 GeV are allowed for certain lifetime ranges, and that a gluino of mass greater than about 4 GeV is allowed with certain lifetimes in the range greater than about 10^{-10} seconds. Some of the experiments cited above claim that the allowed regions are smaller.

The searches discussed above run into potential difficulties either because of non-perturbative hadronic uncertainties, or because of the possibility of a long gluino lifetime. High E_T jet physics has the potential to skirt around some of these difficulties. This is mainly because the essential physics is perturbative, and the final result is rather insensitive to the mass of the light gluino. In this letter, we investigate whether jet production data in $\bar{p}p$ collisions can be used to differentiate between the Standard Model and the Standard Model plus a light, long lived, gluino.

In ep collisions, gluinos do not participate in the hard scattering, and their effect on the quark distributions has been found to be negligible [9, 10]. In contrast, jet production in $\bar{p}p$ collisions is sensitive to the gluino at leading order in perturbation theory. One might suspect the effect on jet cross sections to be rather large since a single Majorana gluino, in many cases, has the same effect as three light quarks. Below, we estimate the effect of a light gluino on $\bar{p}p$ jet production rates by calculating the single-jet-inclusive E_T spectrum. We will show that competing effects tend to suppress the effect of a light gluino.

Before proceeding, it is worth noting a few of the assumptions implicit in our work. First,

we assume that gluinos, if they exist, are sufficiently long lived that they will hadronize and form jets in the same manner as other strongly interacting particles. We furthermore assume that the missing energy resulting from gluino decay into photinos or other weakly interacting particles is negligible. We also assume that other strongly interacting supersymmetric particles, such as squarks, are sufficiently heavy that their effects can be neglected; the presence of a few hundred GeV squark would lead to a peak in the dijet mass distribution not predicted by Standard Model physics [12]. (As yet, no such peak has been established [13] in the data.)

The layout of this letter is as follows. In Sec. 2, we discuss the effects of a light gluino on the single-jet-inclusive E_T spectrum. In Sec. 3, we review the relevant experimental results, and discuss what can be said about a light gluino on the basis of our calculation. Sec. 4 concludes.

2 Light gluinos and the jet E_T spectrum

In order to estimate the effect of a light gluino on the single-jet inclusive cross section we have modified the jet Monte Carlo program JETRAD [14] to include gluinos both in the evolution of α_s and in the hard scattering processes. Parton densities for the proton that include a gluino have been obtained from the authors of Ref. [9]. All of the calculations presented here have been performed to leading order in the QCD coupling parameter, α_s , using a two-loop running of the coupling. In order to match to CDF parameters, the computation was performed for transverse energies, E_T , in the range $50 \text{ GeV} < E_T < 450 \text{ GeV}$ and for pseudorapidities, η , in the range $0.1 < |\eta| < 0.7$. Following standard choices, the renormalization and factorization scales have been set equal to one half of the E_T of the leading jet.

Since we are primarily interested in the effect of a gluino on the shape of the E_T spectrum, leading order perturbation theory is sufficient for our purposes. For standard QCD, the main effect of next-to-leading order corrections is to rescale this cross section by a nearly constant ‘ K -factor’ over the entire range of E_T [15]. (Using JETRAD we have verified this with the above choice of parameters.)

The light gluino has three main effects on the jet E_T spectrum: it modifies the running of α_s , introduces new states into the scattering process, and modifies the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) [16] evolution of the parton densities. In order to obtain a proper estimate of the effect we must include all three of these effects as they are equally important. Below we consider how each of these three effects alter the theoretical prediction of the single-jet-inclusive cross section. We shall find that although the first two tend to increase the cross section preferentially in the high E_T region, the inclusion of a gluino in the parton distributions tends to cancel part of this increase.

The evolution of the coupling constant is controlled by the beta-function

$$\beta_g = \frac{g^3}{16\pi^2} \left[-\frac{11N_c}{3} + \frac{2}{3}n_f + \frac{2N_c}{3}n_{\tilde{g}} \right] + \mathcal{O}(g^5), \quad (1)$$

where n_f is the number of quarks, $n_{\tilde{g}}$ is the number of gluinos which we take to be either zero or one, and $N_c = 3$ is the number of colors. In running the coupling we follow the

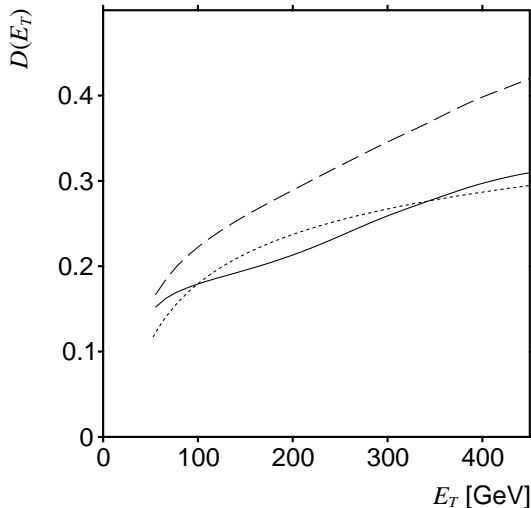


Figure 1: The various contributions of gluinos to the single-jet-inclusive cross section. The dotted line is the effect of only the enhanced coupling. The dashed line includes the effect of the final state gluinos and the enhanced coupling. The solid line includes the previous gluino effects plus the effect on the initial state parton distributions; it is therefore our best estimate of the total effect of the gluino on the cross section.

standard prescription that below a particle threshold the effect of that particle is ignored, but at threshold the contribution to the beta-function is turned on. (To maintain consistency with the conventions of Ref. [9] we take the threshold to be twice the mass of the parton — our final results are insensitive to this choice.) The addition of a light fermionic degree of freedom slows the running of α_s , since it makes the beta function less negative. Indeed, it has been argued that a light gluino could resolve the long-standing but small disagreement between measurements of α_s at low scales (~ 5 GeV) and at high scales (~ 91 GeV) [11].

Starting from the measured value of the strong coupling constant in deep inelastic scattering experiments, a light gluino shifts the value at the Z -resonance from $\alpha_s(M_Z) = 0.110$ to $\alpha_s(M_Z) = 0.122$. These values of α_s are dictated by our choice of parton distribution functions. Since leading order contributions to the single-jet-inclusive production rate are proportional to two powers of α_s , this causes about a 17% rise in the high E_T end of the spectrum. (The coupling constant at about 10 GeV is the same with or without gluinos since it is constrained by the deep inelastic scattering data [17].)

In Fig. 1 we plot the quantity¹

$$D(E_T) = \frac{d\sigma(\text{with } \tilde{g})/dE_T - d\sigma(\text{without } \tilde{g})/dE_T}{d\sigma(\text{without } \tilde{g})/dE_T}, \quad (2)$$

computed with various gluino contributions turned on in the ‘with \tilde{g} ’ part. Since these curves

¹ Throughout this letter we write “ $d\sigma/dE_T$ ” as a shorthand for the quantity $\frac{1}{\Delta E_T} \int_{E_T-\Delta E_T/2}^{E_T+\Delta E_T/2} (\frac{d\sigma}{dE_T}) dE_T$. In the limit $\Delta E_T \rightarrow 0$ this is exact. For all of the graphs presented here $\Delta E_T = 10$ GeV, a value sufficiently small for our purposes.

are generated with a leading order calculation (and because of normalization uncertainties in the experiments), one must be cautious in interpreting the overall normalization; however, the shape of the distribution may be expected to be more robust so that is what we focus on here.

The dotted curve in Fig. 1 represents the case with a gluino enhanced coupling constant, but with conventional QCD matrix elements and parton distributions. These results have been calculated using the MRSD0' [18] partons, for which the fitted value of $\alpha_s(M_Z)$ is 0.110. We use the MRSD0' partons as a reference point in order to maintain consistency with the parton distributions of Ref. [9] which incorporate gluinos, and which will be used below. Observe that although the modified running of α_s gives an upward tilt to the E_T spectrum, most of the rise is concentrated in the lower energy range. We note in passing that the 17% enhancement obtained here using two-loop evolution of α_s is reduced to 14% if one-loop evolution is used.

The second contribution to the jet cross section comes from the fact that the gluinos can participate in the hard scattering. Modern methods for computing QCD and supersymmetric amplitudes can be found in Ref. [19]. For completeness, we list the relevant squared matrix elements (summed over all helicities and colors) as follows,

$$\begin{aligned}
\sum_{\text{spins}} \sum_{\text{colors}} |\mathcal{A}_4^{\text{tree}}(1_{\bar{q}}, 2_q, 3_{\bar{g}}, 4_{\bar{g}})|^2 &= 4g^4 N_c (N_c^2 - 1) \frac{(t^2 + u^2)}{s^2}, \\
\sum_{\text{spins}} \sum_{\text{colors}} |\mathcal{A}_4^{\text{tree}}(1_g, 2_g, 3_{\bar{g}}, 4_{\bar{g}})|^2 &= 4g^4 N_c^2 (N_c^2 - 1) (u^3 t + t^3 u) \left(\frac{1}{s^2 t^2} + \frac{1}{t^2 u^2} + \frac{1}{s^2 u^2} \right), \\
\sum_{\text{spins}} \sum_{\text{colors}} |\mathcal{A}_4^{\text{tree}}(1_{\bar{g}}, 2_{\bar{g}}, 3_{\bar{g}}, 4_{\bar{g}})|^2 &= 8g^4 N_c^2 (N_c^2 - 1) \left[\frac{s^2}{t^2 u^2} (t^2 - ut + u^2) \right. \\
&\quad \left. + \frac{t^2}{s^2 u^2} (s^2 - su + u^2) + \frac{u^2}{s^2 t^2} (t^2 - st + s^2) \right].
\end{aligned} \tag{3}$$

Here,

$$s = (k_1 + k_2)^2, \quad t = (k_1 + k_4)^2, \quad u = (k_1 + k_3)^2, \tag{4}$$

are the usual Mandelstam variables. We use the convention that all particles are in the final state, and the squared matrix elements do not include phase space symmetry factors. Since the typical energy scales probed in jet physics are much higher than the masses of the individual fermions, it is a reasonable approximation to treat the lighter quarks and the gluino as massless. The standard QCD squared matrix elements may be found, for example, in Ref. [20]. (As is usual in jet calculations, we have ignored the top quark.)

Including the effect of gluinos in the final states together with the enhanced coupling we obtain the dashed line in Fig. 1. Thus, by ignoring the effect of the light gluino on the initial state partons we obtain an overall enhancement of the cross section as well as an overall upward tilt in the E_T spectrum, on the order of 26%. Similar upward tilts have been presented in Refs. [21].

Finally, the gluino also modifies the parton densities of the proton. The gluino affects these densities in two ways. In the DGLAP equations there are new channels, and there is also an overall increase in their rate of evolution due to the larger coupling constant.

The effect of a low mass gluino on parton densities has been considered in Refs. [9, 11, 10]. A light gluino has a negligibly small effect on deep inelastic scattering data, including the kinematic region explored at HERA [9, 10]. This is because deep inelastic scattering is sensitive primarily to the quark distributions, and these distributions are quite insensitive to the introduction of a light gluino. The effect of the gluino on the gluon distribution is much larger, but deep inelastic scattering is rather insensitive to the gluon component of the proton.

Since gluons participate directly in the hard scattering at $\bar{p}p$ colliders (dominating the low x contribution), jet production is sensitive to the gluon density in the proton. Modifications to the gluons, therefore, cannot be ignored. The solid line in Fig. 1 shows the complete effect of including a 5 GeV gluino; it includes the modified coupling, the new matrix elements and modified parton distribution functions. (Below we discuss the effect of reducing the gluino mass.) This set of partons² was generated by the authors of Ref. [9], by modifying the analysis used to obtain the standard MRSD0' structure functions.

The fact that the solid line in Fig. 1 shows a smaller rise than the dotted and dashed lines, as we look from low to high E_T , can be traced back to the softening of the gluon and quark distribution functions in the presence of a gluino. By softening we mean that the distribution functions carry less of the proton's momentum and are shifted to smaller x .

The u and d quark densities at moderate x are reduced primarily as a result of the larger value of α_s in the presence of the gluino. This larger value of α_s leads to a more rapid evolution of the quark densities, which in turn reduces the quark densities by a few percent at factorization scales $\mu_F \sim 200$ GeV and x greater than about 0.1.

The gluon distribution is reduced by the larger value of α_s and the fact that gluons can 'split' into gluinos under the DGLAP evolution. This leads to a reduction of about 10% in the gluon density at factorization scales μ_F of order 100 GeV. In Fig. 2 we display the gluon momentum distribution with and without a light gluino. We give the gluon distributions for two factorization scales, $\mu_F = 25$ and 225 GeV; these span the scales probed by the Tevatron single-jet-inclusive experiments.

The effect of this softening on the E_T spectrum is displayed in Fig. 3. Here we show, as in Fig 1, the fractional change in the jet E_T spectrum using the gluino-modified parton distributions of Ref. [9], omitting all other effects of the light gluino. In other words, we have plotted the standard QCD processes convoluted with the Standard Model subset of the modified parton distributions, and adopted the standard (MRSD0') running of the coupling. This shows the origin of the cancellation seen in Fig. 1: the gluon and quark distributions become softer.

Of course, this downward shift in the cross section is reduced somewhat when initial state gluino scattering is included in the calculation. The cross section for gluino scattering is displayed in Fig. 4 for the case of a 5 GeV gluino. We see that this portion of the cross section is significant only at low E_T , and falls off much more rapidly than quark and gluon scattering cross sections with increasing E_T . Thus, in this case initial state gluinos lead to a negligible increase in the high E_T end of the spectrum. The sharp falloff of the gluino contributions may be understood from the fact that at high x there is little gluino component

²We thank R.G. Roberts for making these partons available to us.

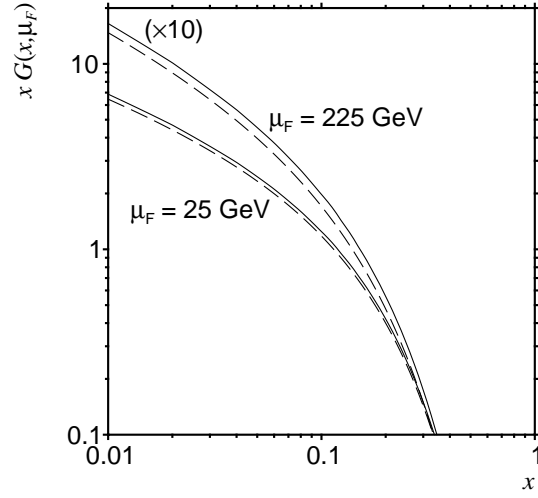


Figure 2: The softening of the gluon distribution function due to gluinos. The solid lines give the gluon distribution of the MRSD0' partons, and the dashed lines are the gluon distributions of Ref. [9] which include the effects of a 5 GeV gluino. The distributions are given for two different factorization scales, μ_F .

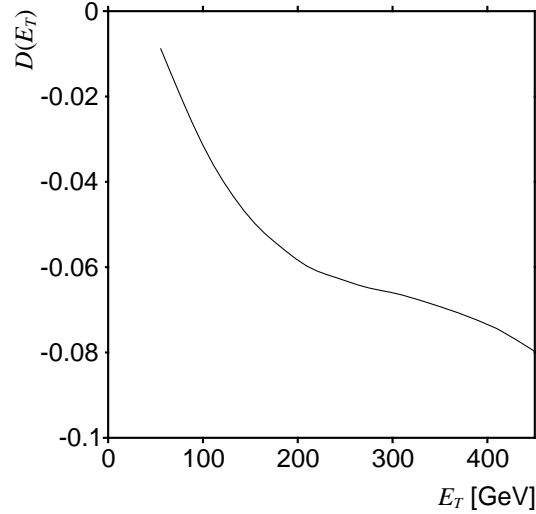


Figure 3: The fractional decrease in cross section due to the softening of the gluon distribution of Ref. [9] as compared to that of MRSD0'.

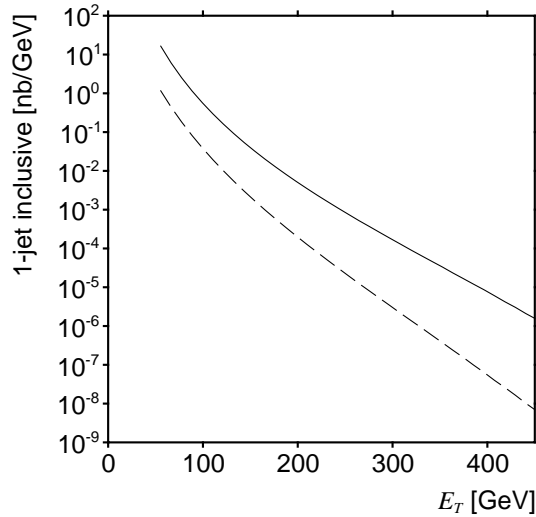


Figure 4: The contribution of the initial state gluinos to the cross section is small, especially in the high E_T region. Here we use the parton distributions of [9] breaking the total single-jet rate into two pieces: the solid curve shows the contribution of the Standard Model initial states scattering to all final states; the dashed curve is that for initial states involving one or more gluinos. The quantity plotted is the differential cross section for the production of individual jets with a given E_T as a function of E_T . It is further divided by the range in pseudorapidity, $\Delta\eta = 1.2$ (for CDF).

to the parton distribution functions; furthermore there is no s -channel scattering of gluinos and quarks, whose distribution is sizeable at high x .

The results presented so far assume a 5 GeV gluino mass, but we are primarily interested in gluinos with a mass of order 1 GeV. We expect that the effects described above will persist for smaller gluino masses for the following reasons.

Firstly, as we saw above, the introduction of a gluino gives an upward tilt to the jet E_T spectrum through the modified running of α_s , and the introduction of new final states in quark and gluon scattering. Both of these effects are largely unchanged if we reduce the gluino mass from 5 GeV to 1 GeV.

Secondly, we note that the quark distributions are determined by fitting to deep inelastic scattering data, and are very weakly modified by the introduction of a light gluino [9, 10]. As these distributions are evolved to higher factorization scales, they are modified somewhat by the larger value of α_s . However, this effect is largely independent of the gluino mass. As a result, a lower gluino mass can only result in a smaller gluon density inside the proton, compensated for by a larger gluino density. In the same way as was found above, the reduction in the gluon density may be expected to lessen the upward tilt in the single-jet-inclusive E_T spectrum. To see this, we note that the parton densities inside the proton are only logarithmically sensitive to the gluino mass. For the enhanced gluino content of the proton to overcome the decrease in the gluon content, from Fig. 4, we would require as a lower bound an order of magnitude increase in the high x gluino distribution. The relatively weak dependence of the gluino density on the gluino mass precludes such a large enhancement. As a crude estimate of the dependence of the gluino density on the gluino

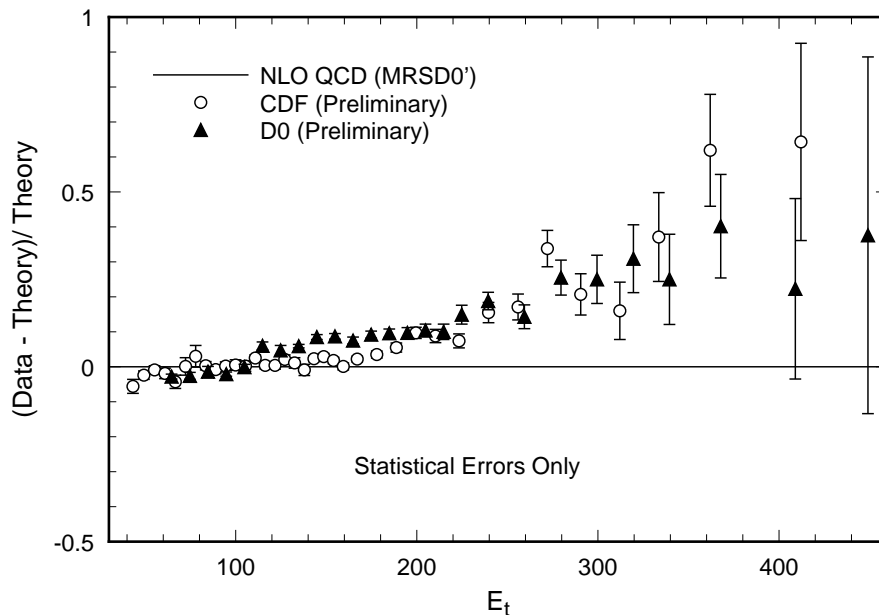


Figure 5: The difference between experiment and NLO theory at 1.8 TeV center-of-mass using the EKS [24] program (from Ref. [23]).

mass, we have evolved the CTEQ3L parton distributions [22] between factorization scales of 2 and 100 GeV, including gluinos of various masses. For gluinos in the 2 to 10 GeV mass range, we see a $\sim 40\%$ variation in the gluino density at factorization scales $\mu_F \sim 100$ GeV. This mild variation is consistent with the gluino mass-dependence found in Ref. [10]. Hence, one expects the cancellation between contributions found above to persist for lower gluino masses. Consequently, we put an upper bound of about 16% on the expected rise in the cross section between low and high E_T due to a light gluino.

3 Relation to Current Experimental Situation

The CDF experiment has reported an excess for the single-jet-inclusive rate at high E_T , of the order of 50%. D0 has not confirmed this excess, but it has been argued elsewhere [23] that, when analyzed with a common theoretical calculation, the D0 data are not found to be inconsistent with that of CDF. In Fig. 5 (which is reproduced from Ref. [23]), the observed signal is seen to be gently rising above the next-to-leading-order Standard Model theory with increasing E_T .

Considering that the cross section falls about seven orders of magnitude over the E_T range of the plot, the agreement between QCD and the data is rather impressive. Nevertheless, the high E_T excess is troublesome. Its interpretation is not clear because of a variety of experimental and theoretical issues [25]. On the theoretical side, for example, it is possible to readjust the parton distribution functions to remove the excess with only a minor penalty

in χ^2 for the global fit to data [23, 26].

The high E_T rise in the CDF data appears to be of the order of 50%, which may be contrasted to the smaller $\sim 16\%$ rise (between low E_T and high E_T) which we found to be due to the light gluino. Thus, we conclude that a light gluino is insufficient to generate the excess observed by CDF. Note also, from Fig. 1, that much of the increase due to a light gluino would occur in the lower energy region, which is not apparent in the CDF data shown in Fig. 5.

Unfortunately, due to the present uncertainties in both the proton's gluon distribution [26] and the systematic experimental uncertainties in the available data, no definitive conclusion is currently possible as to the origin of the rise. With smaller uncertainties it would be possible to rule out or support the existence of a light gluino, or differentiate between other physics scenarios. It would have been desirable to use the data to put bounds on the appearance of extra light strongly interacting degrees of freedom; however, remaining uncertainties in the latest parton distribution functions and the small size of the effect make this task problematic.

One may, of course, increase the high E_T end of the theoretical prediction by assuming particular higher energy scale physics [27]. Unfortunately, there is little constraint on how to go about doing this. Generally, new high scale physics (with appropriately chosen parameters) increases the cross section because new channels open.

In principle it should be possible to determine whether the high E_T rise is due to low (< 5 GeV) or high scale (> 200 GeV) physics. Low energy physics, such as modifications to the parton distributions [26] or the addition of a light gluino, would require that the behavior of the cross section at 630 GeV total center of mass energy be similar to that shown in Fig. 1 for the 1.8 TeV data; essentially one need merely rescale E_T in Fig. 1 by 630/1800. The origin of this simple scaling is that the parton distribution functions undergo little evolution between the energy scales of interest. Although the authors of Ref. [28] have cautioned against direct comparison of perturbative QCD with their 630 GeV data, these data have been found [26] to agree reasonably well with the next-to-leading-order prediction. The UA2 data do not show a rise at high E_T .

In addition, we have investigated the effect of a light gluino on the single-jet-inclusive rate at the pp collider LHC ($\sqrt{s} = 14$ TeV). Over the E_T range 400 GeV to 2 TeV, and with similar cuts on the pseudorapidity of the jet, we find that the full $D(E_T)$ ratio is a slowly decreasing function of E_T . Over this range in transverse energy, $D(E_T)$ falls by roughly 7%.

4 Summary and Discussion

We have estimated the effect of a light gluino on the single-jet-inclusive production cross section measured at CDF [29], D0 [30], and UA2 [28]. The gluino affects this cross section in three ways. Firstly, the gluino slows the running of α_s , making it larger at high energies. This acts to enhance the cross section relative to standard QCD. Secondly, gluinos can be pair produced in $\bar{q}q$ and gg collisions, resulting in a further enhancement of the cross section. (These two contributions have very recently been discussed in Ref. [21].) Finally, the gluino modifies the DGLAP evolution of the parton densities of the proton through the introduction

of new states as well as the value of α_s . We have found that this last effect cancels against the first two, leaving no more than a 16% enhancement between the low and high E_T ends of the spectrum for the case of a 5 GeV gluino. We have argued that this cancellation should persist for smaller gluino masses.

The current experimental uncertainties, and the uncertainties in the parton densities [26], make it unlikely that single-jet-inclusive data will be useful to differentiate between the Standard Model and supersymmetric models with a light gluino.

Acknowledgments

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